

ATOMIC STRUCTURE STUDIES USING FAST-ION SPECTROSCOPY

BY

BOËL DENNE



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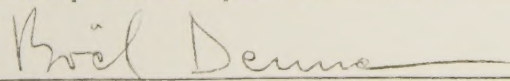
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Title and subtitle Atomic Structure Studies Using Fast-Ion Spectroscopy		
Abstract The method of fast-ion spectroscopy has been used for studies of atomic structure. Spectra and lifetimes for highly ionized O, Al and Cl have been investigated using the beam-foil technique. Selected energy levels and lifetimes have been determined in Ga II. This study was motivated by fusion interest, as was the measurement of the lifetimes of the $4p\ ^2P^0$ levels in Mo XIV. Intercombination transition probabilities have been determined for the $2s^2\ ^1S_0 - 2s3p\ ^3P_1^0$ line in N IV, O V and F VI and for the $1s^2\ ^1S_0 - 1s2p\ ^3P_1^0$ transition in He-like O VII and F VIII. A shortening of the lifetime of the $1s2p\ ^3P_0^0$ level in F VIII and Al XII due to a hyperfine-induced decay to the ground level has been observed. Relative level populations in beam-foil-excited C IV, N V, O VI and F VII have been studied in the range $n = 3 - 12$. The method of beam-tilted-foil excitation has been applied to O IV and O VI. The circular polarization has been studied as a function of the foil tilt angle. The fine structures in the $nd\ ^2D$, $n = 4, 5$ and $nf\ ^2F^0$, $n = 4, 5, 6$ levels in Be II have been measured using the fast-beam level-crossing technique and compared with calculated hydrogenic intervals.		
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ATOMIC STRUCTURE STUDIES USING
FAST-ION SPECTROSCOPY

av

BOËL DENNE

fil. kand., Hb.

AKADEMISK AVHANDLING

som med vederbörligt tillstånd

av matematisk-naturvetenskapliga fakulteten vid Lunds universitet

kommer att för avläggande av filosofie doktorsexamen

offentligen försvaras å fysiska institutionens föreläsningssal B

fredagen den 25 september 1981 kl. 10.15



To my Mother and Father

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1. INTRODUCTION AND SUMMARY

The subject of this thesis is the study of atomic structure using fast-ion beams.

The thesis consists of 12 papers, 11 of which deal with experiments using the beam-foil technique and one utilizing the fast-beam level-crossing technique. The beam-foil experiments have been performed in Lund, Stockholm, Uppsala and Aarhus and the fast-beam level-crossing experiment in Aarhus.

Individual summaries of the papers will be given in this section. In Chapter 2 the beam-foil experimental setup will be described in detail, in Chapter 3 the experimental results concerning lifetimes and energy levels (Papers 2-9 and 12) will be discussed whereas the beam-foil excitation mechanism is the subject of Chapter 4 (Papers 1 and 11). Chapter 5, finally, gives a short description of the fast-beam level-crossing technique (Paper 10).

The papers are:

1. Observation of Strong Orientation Effects for Levels in Highly Ionized Oxygen.

S. Huldt, L.J. Curtis, B. Denne, L. Engström, K. Ishii and I. Martinson
Physics Letters 66 A, 103 (1978)

2. Lifetime Measurements for some $\Delta n = 0$ Transitions in Cl XIII - Cl XV.

K. Ishii, E. Alvarez, R. Hallin, J. Lindskog, A. Marelius, J. Pihl,
R. Sjödin, B. Denne, L. Engström, S. Huldt and I. Martinson
Physica Scripta 18, 57 (1978)

3. Energies and Lifetimes of the $4s4d\ ^1D$ and $4p^2\ ^1D$ in Ga II.

B. Denne, U. Litzén and L.J. Curtis
Physics Letters 71 A, 35 (1979)

4. Experimental Transition Probabilities for Intercombination Lines in N IV, O V and F VI.

L. Engström, B. Denne, S. Huldt, J.O. Ekberg, L.J. Curtis, E. Veje and
I. Martinson
Physica Scripta 20, 88 (1979)

5. Radiative Lifetimes of Highly Ionized and Foil-Excited Al.
 B. Denne, D.J. Pegg, K. Ishii, E. Alvarez, R. Hallin, J. Pihl and R. Sjödin
 Journal de Physique Colloque C1, Suppl. 40, C1-183 (1979)
6. Beam-Foil Studies of Multiply Ionized Oxygen.
 B. Denne, L. Engström, S. Huldt, J.O. Ekberg, L.J. Curtis, K. Ishii, E. Veje and I. Martinson
 Physica Scripta 21, 151 (1980)
7. Radiative Lifetimes and Hyperfine Induced Decay of the $1s2p\ ^3P_2$ and 3P_0 Levels in Al XII.
 B. Denne, S. Huldt, J. Pihl and R. Hallin
 Physica Scripta 22, 45 (1980)
8. Lifetimes of the $1s2p\ ^3P_0$ and 3P_2 Levels in F VIII.
 L. Engström, C. Jupén, B. Denne, S. Huldt, Weng Tai-Meng, P. Kaijser, U. Litzén and I. Martinson
 Journal of Physics B: Atomic and Molecular Physics 13, L143 (1980)
9. Transition Probabilities for Allowed and Forbidden Transitions from the $1s2p\ ^3P$ Levels in He-like O VII and F VIII.
 L. Engström, C. Jupén, B. Denne, S. Huldt, Weng Tai-Meng, P. Kaijser, J.O. Ekberg, U. Litzén and I. Martinson
 Physica Scripta 22, 570 (1981)
10. Fine Structures of the $nd\ ^2D$ and $nf\ ^2F$ Sequences in Singly Ionized Beryllium.
 B. Denne, H. Dickow and O. Poulsen
 Physical Review A 23, 214 (1981)
11. Relative Level Populations in Beam-Foil-Excited C IV, N V, O VI and F VII.
 B. Andresen, B. Denne, J.O. Ekberg, L. Engström, S. Huldt, I. Martinson and E. Veje
 Physical Review A 23, 479 (1981)

12. Radiative Lifetimes of the $4p\ ^2P_{1/2}$ and $^2P_{3/2}$ Levels in the Mo XIV.

B. Denne and O. Poulsen

Physical Review A 23, 1229 (1981)

Paper 1 is a study of the polarization of the emitted light after beam-foil excitation using the tilted-foil geometry. The circular polarization for the $n = 6 - 7$ transition in O VI at 3433 Å and the $2p3p\ ^4D - 2p3d\ ^4F^o$ transition in O IV at 3737 Å has been measured as a function of the foil tilt angle.

Paper 2 is a beam-foil investigation of chlorine at energies up to 48 MeV in the wavelength region 300 - 1100 Å. Hydrogenic transitions, as well as $\Delta n = 0$ transitions, belonging to Cl XII - Cl XV were observed. The transition probabilities were measured for four important $\Delta n = 0$ transitions in Li-, Be- and B-like Cl.

Paper 3 reports on a combined classical spectroscopy - beam-foil excitation experiment in Zn-like Ga II. Four new classifications of 1D and 1S levels in Ga II have been made with a sliding spark source and the lifetimes of the $4s4d\ ^1D$ and $4p^2\ ^1D$ levels have been measured using beam-foil excitation. Studies of the level schemes and oscillator strengths for members of the Zn I isoelectronic sequence are motivated by fusion interest, since its highly-ionized members have been observed in tokamak plasmas. However, the level schemes and lifetimes are incompletely known even in the beginning of the sequence, a fact which initiated this work.

Paper 4 discusses the intercombination transition $2s^2\ ^1S_0 - 2s3p\ ^3P_1^o$ in Be-like N IV, O V and F VI. Using the beam-foil technique the individual lifetimes for the $2s3p\ ^3P_{0,1,2}^o$ levels were carefully measured. The $^3P_1^o$ lifetime was found to be considerably shorter than those of the other two $^3P^o$ levels. This is due to the intercombination line. By comparing the lifetimes of all three levels, the transition probabi-

lity of the intercombination line could be determined.

Paper 5 is an investigation of highly-ionized aluminium. Spectra in the range 300 - 1000 Å were recorded at 10, 20, 30 and 45 MeV beam energies. Radiative lifetimes for some of the low-lying levels in Li-, Be- and B-like Al were measured using the beam-foil method.

Paper 6 is a study of O IV - O VII. Spectra in the wavelength region 2000 - 4500 Å have been recorded at 2, 4.5, 6 and 9 MeV using a refocussed spectrometer to obtain good spectral resolution. One of the goals of the present study was to determine the wavelengths more accurately than in previous beam-foil investigations. Several new hydrogenic transitions were observed. The data were compared with predictions using polarization formulae and confirmed previous estimates of dipole and quadrupole polarizabilities. A few lifetimes in O IV - O VI are also reported.

Paper 7 reports on the first observation of the $1s2s\ ^3S_1 - 1s2p\ ^3P_2^o$ and $1s2s\ ^3S_1 - 1s2p\ ^3P_0^o$ transitions in He-like Al XII. The wavelengths were measured with an accuracy of ± 1 Å and were in good agreement with theoretical values which include Lamb shift. The lifetimes of the upper levels were determined. A shortening of the $2p\ ^3P_0^o$ lifetime was observed, in agreement with theories which consider hyperfine quenching effects. An estimate of the quenching is given in the paper.

Paper 8 is a verification of the hyperfine quenching effect discussed in Paper 7. Experimental lifetimes are reported for the $1s2p\ ^3P_0^o$ and $1s2p\ ^3P_2^o$ levels in He-like F VIII. A value for the quenching of the $3P_0^o$ level was obtained in very good agreement with theory.

Paper 9 is an extension of the work reported in Paper 8. The lifetimes of the $1s2p\ ^3P_{0,1,2}^o$ levels in F VIII and of $1s2p\ ^3P_{1,2}^o$ in O VII have been measured. Experimental transition rates for the $1s^2\ ^1S_0 - 1s2p\ ^3P_1^o$ intercombination transition have been deduced as well as for the nu-

clear-spin induced $1s^2\ ^1S_0 - 1s2p\ ^3P_0^o$ transition in F VIII. All results are in good agreement with recent theoretical calculations.

Paper 10 reports on a measurement of the fine structures in the $nd\ ^2D$, $n = 4, 5$ and $nf\ ^2F^o$, $n = 4, 5, 6$ levels in Be II using the fast-beam level-crossing technique. The fine structure splittings have been determined to within 10^{-3} . By comparing the experimental results with the calculated hydrogenic intervals, this precision allowed the establishment of a non-hydrogenic behaviour for the $4f\ ^2F^o$ level, whereas the $nd\ ^2D$ levels were found to be almost purely hydrogenic, within error limits, as was the case for the $5f\ ^2F^o$ and $6f\ ^2F^o$ levels. The present study thus indicated normal fine structure in Be II. The small deviations from hydrogenic fine structure could be attributed to correlation effects involving the $(1s^2)$ core.

Paper 11 is a study of the relative level populations in beam-foil-excited C IV, N V, O VI and F VII by optical spectrometry in the range $n = 3 - 12$. These Li-like ions have the configuration $1s^2n\ell$. The population distribution curves are quite different, ranging from a sharp, approximately $(n^*)^{-3}$, decrease for C IV to flat maxima at $n \sim 7$ and 8 for O VI and F VII, respectively. This gradual change may be explained as resulting from a near-resonant charge transfer from the valence band of the carbon foil to the projectile. For a fixed value of n , the relative level population increases more rapidly with the ℓ - value than as the statistical weight $(2\ell + 1)$. Superimposed on this increase, there is a preferential population of p levels.

Paper 12 is a measurement of the lifetimes of the upper levels of the resonance transitions in Mo XIV, $4s\ ^2S_{1/2} - 4p\ ^2P_{1/2,3/2}^o$. The study of highly-ionized molybdenum is of particular interest since this element is often used as a construction material in tokamaks. The evaluation of the lifetimes from the recorded decay curves posed a special problem since the curves were strongly affected by cascades. The present

ce of blends in the cascading transitions prevented the use of the ANDC-technique. Instead decay curves were computer-simulated and fitted to the experimental data. Different population models were investigated to fit the data. The lifetimes obtained were in good agreement with theoretical calculations. However, with the present level of accuracy, it was not possible to differentiate between the various theoretical approaches.

Spectra were also recorded in the wavelength region 80 - 430 Å at every 5 MeV between 5 and 25 MeV beam energy.

2. EXPERIMENTAL ARRANGEMENT

The following sections describe the experimental equipment used at the University of Lund for the experiments reported in Papers 1,4,6,8,9 and 11.

2.1 The Pelletron accelerator

The model 3 UDH Pelletron accelerator, manufactured by the National Electrostatics Corporation (NEC), was delivered to Lund in 1975. This accelerator, which is of the tandem type, has a maximum terminal voltage of 3 MV. A direct extraction duoplasmatron ion source is used to produce a negative ion beam, which is then pre-accelerated to an energy of 40 keV. This type of source requires that the element of which an ion beam is to be formed is obtainable from a gaseous or volatile liquid compound and also easily produces negative ions. Thus CO_2 has been used to produce O^- , $\text{SF}_6 + \text{H}_2$ for F^- and $\text{CO}_2 + \text{N}_2 + \text{H}_2$ for CN^- (used for work both on C and N).

The beam is mass-analysed in an inflection magnet and enters subsequently into the accelerator tube. In the high-voltage terminal electrons are stripped off by means of a carbon foil or a gas (O_2). When the accelerator has been used to produce heavy-ion beams for the beam-foil work, the gas stripper has been preferred, since the carbon foils tend to break after a short time when bombarded with heavy ions of relatively low energy (0.7 - 2.5 MeV).

The now positive ion beam enters into the analysing magnet which is used for energy analysis as well as for directing the beam down one of the five beam-lines. The beam-line used for our work has an angle of 20° with respect to the beam axis before the analysing magnet. For this beam-line the mass-energy product is 210, which enables the use of elements within the total energy range of the accelerator.

Technical and other details of the Pelletron accelerator system can be found in Ref. 1.

2.2 The beam-foil target chamber

After emerging from the analysing magnet the ion beam enters into the target chamber after passing through a magnetic quadrupole for beam focussing.

The target chamber is an O-ring-sealed aluminium box with the interior dimensions $140 \times 155 \times 400$ mm (approx.). The inner walls are covered with black paint in order to reduce reflected light. The self-supporting target carbon foils are mounted on stainless steel frames. Typical foil thicknesses used are $5 - 20 \mu\text{g}/\text{cm}^2$ ($10 \mu\text{g}/\text{cm}^2$ corresponds to a thickness of approximately 500 Å). Commercial foils have been used in most experiments. A foil-wheel, which can carry 20 foils, is mounted on a trolley which can be translated along a precision screw. The screw is turned by means of a stepping motor placed outside the chamber, the axis of the motor being connected to the precision screw via a high-vacuum feed-through. The pitch of the screw is 6 mm. Since the stepping motor makes 96 steps per revolution, the minimum step size is $1/16$ mm. The trolley can travel a distance of 232 mm between two end-point switches, by means of which an absolute calibration of the screw is possible. Via another vacuum feed-through the foil-wheel can be rotated about its axis thus positioning a foil in the beam path and allowing a broken foil to be replaced by a fresh one.

Apart from the entrance and exit ports for the ion beam, the target chamber has three ports to which spectrographs can be connected. Two of the ports are placed opposite to each other in the far down-stream end of the chamber. So far only one of these ports has been used. The third port is placed in the bottom of the chamber at right angles to the other two and is presently unused.

On the top of the chamber there is a large plexi-glass inspection window, making access to the interior of the chamber possible.

The beam enters into the chamber through a fixed brass aperture of 4.5 mm diameter. After passing through the target foil the beam is dumped in a shielded Faraday cup. This cup consists essentially of three parts: a ground-

ed ring, a biased repeller ring (bias: -150 V) and a particle collector connected to a digital current integrator. This type of cup is thoroughly described in Ref. 2. During data-taking the cup is used for normalization by collecting a certain amount of beam charge for each data point. This is done to compensate for beam fluctuations.

2.3 The vacuum system

The beam-line between the analysing magnet and the target chamber and the target chamber itself are efficiently pumped by two large diffusion pumps. These pumps allow a quick evacuation of the beam-line and chamber. Typical final vacuum is better than 10^{-6} torr.

All vacuum valves, except two hand-manoeuvred ones on the beam-line, are pneumatically operated and connected to the vacuum-guard system of the accelerator (see Ref. 1).

2.4 The spectrographs

The spectrographs (monochromators) which have been used in Lund are:

a 0.35 m McPherson EUE - 700 monochromator (Paper 1)

a 1 m McPherson model 2051 grating monochromator (Papers 4,6 and 11)

a 1 m Minuteman 310 NIV normal incidence vacuum monochromator (Papers 8 and 9)

The vacuum monochromator is pumped by a large diffusion pump, maintaining a vacuum of better than 10^{-6} torr. The entrance slit assembly of this monochromator has been redesigned enabling the entrance slit to be placed inside the target chamber. With this arrangement the beam-to-slit distance is reduced, thus increasing the spatial (temporal) resolution. The new slit assembly is described in Ref. 3.

The two air instruments were optically connected to the target chamber.

Since the beam particles move with a speed of typically a few percent of the speed of light, the emitted light is subjected to Doppler effects which can be large. By viewing at an angle of 90° to the beam direction the first

order Doppler shift can be eliminated, while the second order Doppler shift prevails. More serious is the line broadening caused by the finite acceptance angle of the spectrometer. Several methods to overcome this problem have been worked out. The method of refocussing of the spectrometer suggested by Stoner and Leavitt [4] has been used in Lund. With this method the line broadening can be efficiently reduced by moving the exit slit an additional distance d away from the grating, or by moving the grating a distance $d/2$ away from the entrance and exit slits. The distance d is given by

$$d \cong \frac{v}{c} \cdot \frac{\lambda}{K} \quad (1)$$

where v is the beam particle velocity, c the speed of light, λ the wavelength of the spectral line and K the inverse linear dispersion of the grating. For refocussing of the Minuteman vacuum monochromator the grating was moved along its normal, while the two air instruments were refocussed by making the concave mirror closest to the exit slit movable with respect to this slit, this having the same effect as moving the grating.

In addition to this simple method more powerful, high-intensity methods for refocussing have been developed by Bergkvist [5] and by Jelley et al. [6].

2.5 The detectors

The detectors which have been used in the Lund experiments are:

a Bendix CEM 4503 channel electron multiplier for wavelengths between 300 and 1100 Å

an EMR model 541F-08-18 photomultiplier tube for the wavelength range 1050 Å to 2500 Å

an EMI model 9789 QB photomultiplier for wavelengths between 2000 and 5500 Å.

These detectors have been operated in the photon-counting mode. Typical dark counts have been 0.1 - 0.3/s for the channeltron and the EMR tube, while for the EMI tube it has been about 1/s, provided the tube has been cooled. For cooling dry ice or the cold nitrogen vapours boiled off from a liquid nitro-

gen container have been used.

2.6 The electronics

The detector pulses are pre-amplified by a modified Ortec pre-amplifier and subsequently amplified and discriminated using standard NIM-electronics.

2.7 The data-taking procedure and analysis

Experimental data are taken using an automated on-line system which has been specially designed for fast-ion beam spectroscopy. This system consists of a Computer Automation Alpha-LSI 2/20 minicomputer with a 64 kB core memory, a Tektronix 4006 graphic terminal used for communication as well as for data presentation. An experimental control unit, designed and built at the laboratory handles the communication between the computer and the scalers and end-point switches of the grating and foil drives, as well as the stepping motors used for translating the foil (lifetime measurements) and turning the grating (spectral scans). The communication takes place through a standard input/output interface. This unit is described in Ref. 3.

Programs and experimental data are stored in a unit consisting of two Pertec FD 511 floppy disc drives and a floppy disc controller. Also connected to the data-taking system is a Calcomp 565 digital plotter and a Centronix 101 line printer for data presentation. A paper tape punch and paper tape reader can also be connected. The data-taking system is thoroughly described in Refs. 3 and 7.

An experiment is run using two programs, SOX and EOX. The first one of these is used to initiate a measurement. The specified stepping motors are driven to their initial positions and the motor which is going to be stepped during the experiment and the initial step size is determined. When the program is terminated all information is written on a data disc as a parameter block. The second program, EOX, is the main program for data acquisition and presentation. This program also enables on-line analysis of decay curves (one- and two-exponential fits) and the running of a peak-finding program for

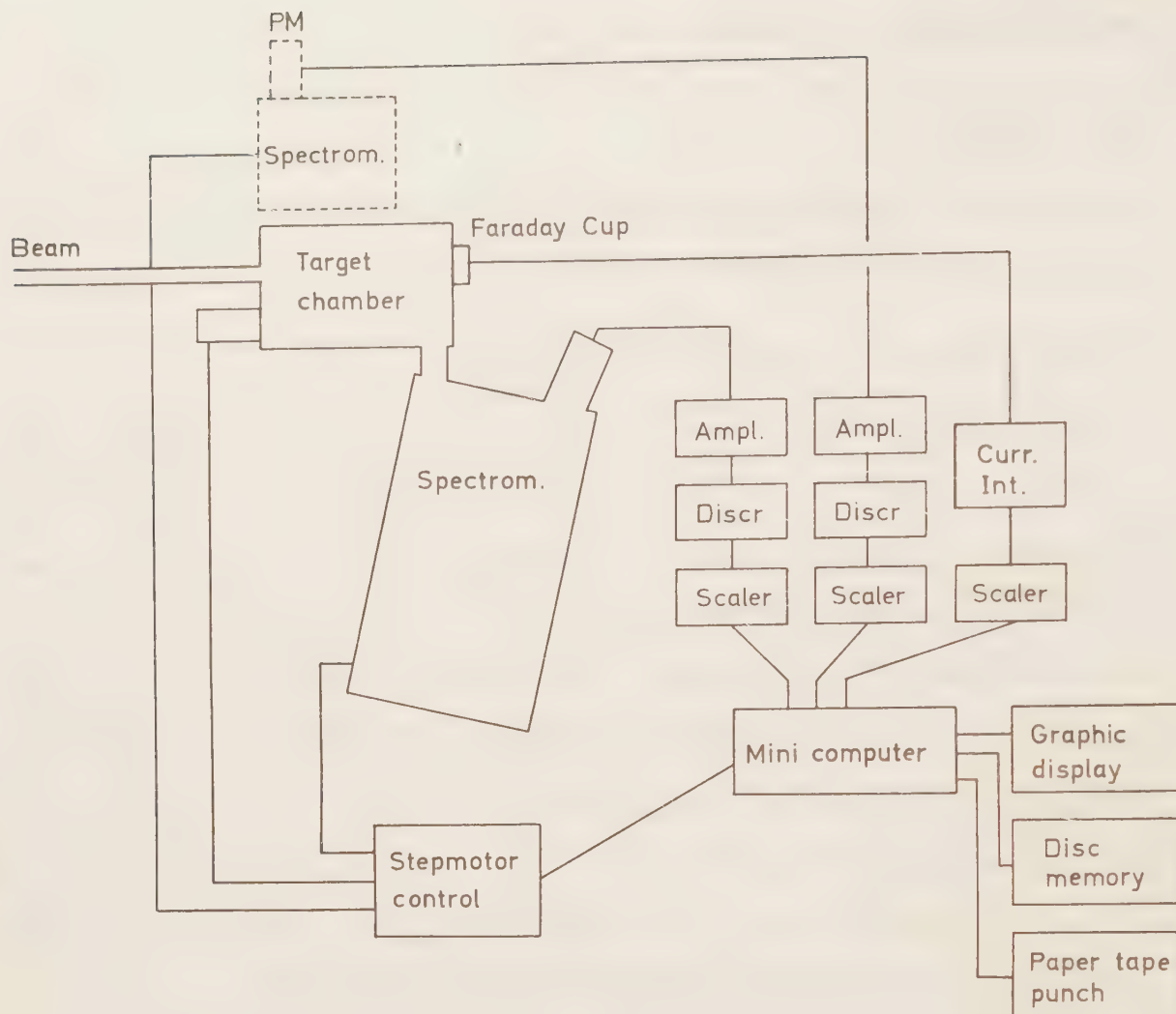


Fig. 1. Schematic outline of the experimental setup used for beam-foil spectroscopy at the University of Lund.

spectrum analysis, as well as on-line plotting of the data. The EOX program is controlled via options that can be given at any time during data accumulation. A detailed description of these two programs is given in Ref. 8. In this reference are also listed some of the off-line programs which are used for data analysis and other purposes. These programs are described elsewhere [9].

Figure 1 shows the general features of the Lund beam-foil experimental setup.

2.8 Experimental systems used at other laboratories

The experiments reported in Papers 2,3,5,7,10 and 12 have been performed at other laboratories.

The 6.5 MV EN Tandem accelerator (High Voltage Engineering Corp.) in Uppsala was used for the work on highly ionized Cl (Paper 2) and Al (Papers 5 and 7). Cl^- ions were produced in a duoplasmatron ion source, using a mixture of Cl_2 and H_2 . The Al beam was supplied by a sputtering ion source, in which Al^- ions were sputtered off an aluminium cone by a beam of positive Cs ions. By introducing O_2 into the ion source, the ion AlO^- was formed and then accelerated. The spectrometer used in these works was a 1 m Seya-Namioka monochromator, designed and built at the Uppsala laboratory.

The 400 kV accelerator (Nucletec S. A., Geneva) at the Research Institute for Atomic Physics (AFI) in Stockholm was used for the lifetime measurements in Ga II, described in Paper 3. Positive Ga ions were produced in a universal ion source. The monochromators used were a 0.35 m Heath EUE - 700 (for air wavelengths) and a 1 m Seya-Namioka (for vacuum wavelengths).

For a detailed description of the experimental setups in Uppsala and Stockholm the reader is referred to [10] and [11].

For the fast-beam level-crossing experiment in Be II (Paper 10) carried out at the University of Aarhus, Denmark, a 80 kV isotope separator was utilized in connection with a universal ion source to produce a positive Be-ion beam. The spectrometer used was a 0.25 m Jobin-Yvon M 25 monochromator.

The experiment in Mo XIV (Paper 12), finally, was done using the 6.5 EN Tandem accelerator in Aarhus. This machine is similar to the Uppsala one mentioned above. Negative molybdenum ions were produced in a sputtering ion source. The ions subsequently accelerated, MoO_2^- or MoO_3^- , were formed by introducing O_2 into the ion source. The spectroscopic instrument in this case was a 2.2 m McPherson model 247 grazing-incidence spectrometer.

The data-taking procedure using the Aarhus systems is briefly described in Ref. 12.

3. BEAM-FOIL SPECTROSCOPY AND LIFETIME MEASUREMENTS

3.1 General

Beam-foil spectroscopy was introduced by Kay [13] and Bashkin [14] in the early 1960's. A beam of positive ions from an accelerator is incident upon a thin target foil, usually consisting of carbon. During the passage through the foil, the ions are abruptly excited (within $\sim 10^{-14}$ s) and they emerge from the foil in different stages of ionization and excitation. The in-flight emitted light from the decaying states can subsequently be spectroscopically investigated.

There are several advantages with the beam-foil light source. Any accelerator producing positive ions can be used. By a proper choice of ion source, practically any element in the periodic system can be accelerated and investigated. Magnetic analysis of the accelerated beam yields a chemically and isotopically pure beam. However, when e.g. isotope separators or single-ended Van de Graaffs are used, molecular ions with approximately the same mass as the atomic ion ($^{16}\text{O}_2^+$ has e.g. nearly the same mass as $^{32}\text{S}^+$) may appear as impurities. This problem is avoided when tandem Van de Graaffs are used, since molecules do not survive the stripping process. By varying the beam energy (i.e. the ion velocity) different stages of ionization are available. A wide range of ion energies has been covered, from a few keV to a few hundred MeV.

The low particle density in the beam (typically 10^5 cm^{-3}) makes interionic fields negligible. Many problems which are encountered using other types of light sources, such as self-absorption and collisional deexcitation, are virtually absent in the beam-foil light source.

The uniqueness of the beam-foil source is its excellent time-resolution. After emerging from the foil the ions have a well-defined uniform velocity v , and thus the time t after excitation corresponds to a distance x down-stream from the foil. The ion velocity v , expressed in mm/ns, is given by

$$v = 13.9\sqrt{E/M} \quad (2)$$

where E is the ion energy in MeV after the foil and M is the ion mass in amu.

The decrease in light intensity as a function of the distance from the foil for a spectral line is a measure of the decrease in population for the upper level of the transition. When cascade repopulation from higher-lying levels is absent the intensity decay can be expressed as

$$I(x) = I(0)e^{-x/v \cdot \tau} \quad (3)$$

where τ is the lifetime of the upper level.

The beam-foil light source also exhibits some disadvantages, one of the most important being the unselective nature of the excitation. This property may make the interpretation of radiative decay curves difficult if the level under study is repopulated by cascades from more highly excited levels.

The low particle densities in the beam-foil light source make the study of weak lines difficult. The light emitted in flight is subjected to Doppler effects, as has been discussed in Chapter 2.4. Such effects along with scattering processes in the foil causes line broadening and may make line-blending a serious problem in spectral analysis. However, as was mentioned in 2.4, methods can be applied to reduce the Doppler-broadening. Foil ageing is another problem. The foil may change its properties with time during ion bombardment and also develop pinholes, which may affect the light-to-beam-current normalization. When heavy ions and low energies are used, foil breakage can also be a serious problem.

There exist several review articles on beam-foil spectroscopy, e.g. Refs. 2 and 15-17.

3.2 Results

In the following two subsections the beam-foil experimental results concerning spectral studies as well as lifetime measurements will be discussed.

3.2.1 Energy levels

In beam-foil excitation levels with high principal quantum number n and orbital angular momentum quantum number ℓ as well as multiply-excited levels are preferentially populated with respect to many other levels.

The high n, ℓ -levels are hydrogenic in character. For a non-penetrating orbit the energy of the level, $E(n, \ell, Z)$, can be described by the polarization formula [18]

$$E(n, \ell, Z) = E_0(Z) - T_H(n, \ell, Z) - \Delta p(n, \ell, Z) \quad (4)$$

where E_0 is the ionization potential and Z the nuclear charge. T_H is the hydrogenic term value given by the relativistic formula

$$T_H = \frac{R \zeta^2}{n^2} \left\{ 1 + \frac{\alpha^2 \zeta^2}{n^2} \left(\frac{n}{\ell + 1/2} - \frac{3}{4} \right) \right\} \quad (5)$$

with R being the Rydberg constant for the element under study, ζ the net core charge and α the fine structure constant. The polarization energy Δp can be expressed as

$$\Delta p(n, \ell, Z) = A(Z)P(n, \ell) [1 + k(Z)q(n, \ell)]. \quad (6)$$

Here $A(Z)$ and $k(Z)$ are constants which are related to the dipole and quadrupole polarizabilities of the core, whereas $P(n, \ell)$ and $q(n, \ell)$ are functions tabulated in Ref. 18. For transitions between two non-penetrating orbits the wavelength is independent of $E_0(Z)$ and can be predicted from $A(Z)$ and $k(Z)$ alone.

A study of transitions between such hydrogenic levels in multiply ionized oxygen is presented in Paper 6. Beam-foil spectra have been recorded at several beam energies in the wavelength region 2000 - 4500 Å with emphasis on good spectral resolution, which was achieved by refocussing of the monochromator according to Ref. 4. Wavelengths for hydrogenic transitions in O IV - O VII have been determined with a higher accuracy than in previous beam-foil studies of these spectra (see references given in Paper 6). Also a number of new lines are reported. Our results confirm previous estimates of dipole and quadrupole polarizabilities. In O·VII a value for the ionization potential has been derived. Agreement is obtained with an earlier value [19], but the uncertainty is somewhat reduced. However, our value is not accurate enough to determine the $1s^2$ ground state Lamb shift, a quantity which can be obtained by comparing accurate theoretical and experimental ionization energies for He-like ions [20-22].

Table I

Transition energy (cm ⁻¹)	
1s2s ³ S ₁ - 1s2p ³ P ₂ ^o	1s2s ³ S ₁ - 1s2p ³ P ₀ ^o
111110 ± 100 ^a	104930 ± 100 ^a
111065 ^b	104722 ^b
111133 ^c	104746 ^c
111534 ^d	105127 ^d

^aPaper 7, experiment

^bPaper 7, theory

^cBerry et al.[23]

^dSafronova [24]

In Paper 6 also a few lifetimes are reported.

In Paper 7 is reported the first measurement of the wavelengths of the 1s2s ³S₁ - 1s2p ³P_{2,0}^o transitions in He-like Al XII. Instrumental limitations caused the accuracy in the wavelength determination to be not better than ±1 Å. However, good agreement was obtained with theoretical transition energies including one-electron quantum electrodynamic (QED) contributions (Lamb shift). Recently, theoretical calculations of the transition energies have been made by Berry et al. [23] and by Safronova [24]. Their results for Al XII are given in Table I together with our results.

3.2.2 Lifetimes

The lifetime τ of a level i is given by the relation

$$\tau^{-1} = \sum_k A_{ik} \tag{7}$$

where A_{ik} is the transition probability between levels i and k . The summation extends over all lower-lying levels k . A lifetime measurement yields the sum of the transition probabilities. To obtain the individual A_{ik} 's, the branchingratios for the different decay channels have to be known. If the level i

can only decay to one level k , the lifetime is the inverse of the transition probability. With the beam-foil method lifetimes in the range from ps to μ s can be measured.

Instead of the transition probability A_{ik} the oscillator strength f is often used. The relation between the f -value and the transition probability for allowed electric dipole transitions is given by

$$f = 1.4992 \cdot 10^{-16} \cdot \lambda^2 \cdot \frac{g_i}{g_k} \cdot A_{ik} \quad (8)$$

where λ is the transition wavelength in Å and g_i and g_k the statistical weights of the upper and lower levels respectively.

The measurement of atomic lifetimes is the subject of Papers 2-5,7-9 and 12.

A few years ago a beam-foil investigation of highly ionized chlorine was performed at the Tandem Accelerator Laboratory in Uppsala by Hallin et al. [10]. Beam energies were varied between 6 and 42 MeV and hydrogenic transitions in Cl VI - Cl XV were observed in the wavelength region 2000 - 5700 Å. Paper 2 is an extension of this work at beam energies up to 48 MeV and concerns the wavelength range 300 - 1100 Å. Lifetimes have been determined for a number of important $\Delta n = 0$ transitions in Li-, Be- and B-like Cl. The transitions studied were the resonance doublet, $2s \ ^2S_{1/2} - 2p \ ^2P_{1/2,3/2}^o$, in Li-like Cl XV, the $2s2p \ ^1P_1^o - 2p^2 \ ^1D_2$ transition in Cl XIV and the $2s2p^2 \ ^2P_{3/2} - 2p^3 \ ^2D_{5/2}^o$ transition in Cl XIII. The decay curves recorded were analysed by fitting a number of exponentials to the data. The lifetimes obtained were in good agreement with theoretical calculations. For the $2s - 2p$ transitions in Cl XV relativistic corrections yield an f -value which is 4 % higher than the non-relativistic one [25]. However, our experimental accuracy was not sufficient for confirming this. Some spectroscopic work was also undertaken. A number of strong hydrogenic transitions belonging to Cl XII - Cl XVI were seen in the spectra. A few new lines were also observed, some of which seemed to belong to lower ionization stages.

$\Delta n = 0$ transitions were also studied in Li-, Be- and B-like Al. This is re-

ported in Paper 5. Spectra in the same wavelength region as in the chlorine case were recorded for 10, 20, 30 and 45 MeV beam energies. The transitions studied were the doublet $2s^2 S_{1/2} - 2p^2 P_{1/2,3/2}^o$ in Li-like Al, the $2s2p^3 P_2^o - 2p^2^3 P_2$ and $2s2p^1 P_1^o - 2p^2^1 D_2$ transitions in Al X and the $2s2p^2^2 P_{3/2} - 2p^3^2 P_{1/2,3/2}^o$ and $2s2p^2^2 P_{1/2} - 2p^3^2 D_{3/2}^o$ transitions in Al IX. Some hydrogenic transitions belonging to these spectra were also identified. The lifetimes of the upper levels were determined by applying the multi-exponential fitting program DISCRETE [26] to the experimental decay curves. Table II, in which the results are summed, is a revised version of Table I in Paper 5. Some errors have been corrected and also additional information has been included. For Al X, the $2p^2^1 D_2$ level can decay to $2s2p^1 P_1^o$, $3P_1^o$ and $3P_2^o$ via electric dipole transitions. By interpolation from the theoretical data given by Mühlethaler and Nussbaumer [33] a branching ratio of 0.98 is obtained for the $2s2p^1 P_1^o - 2p^2^1 D_2$ transition. The remaining 2 % thus represents the decay to $2s2p^3 P_1^o$ and $3P_2^o$. Higher multipole transitions, e.g. to the ground level have been neglected. The f -value obtained, 0.107 ± 0.005 , is in good agreement with theories. In a recent study of Be-like Mg, Al, Si, P and S by Träbert and Heckmann [36] the lifetime of the $2p^2^1 D_2$ level in Al X was measured. The result was 1.080 ± 0.080 ns which agrees with our value of 1.03 ± 0.05 ns.

The $2p^3^2 D_{3/2}^o$ level in Al IX can decay to $2s2p^2^2 P_{1/2}$, $2P_{3/2}$, $2D_{3/2}$, $2D_{5/2}$ and $2S_{1/2}$. The $2s2p^2^2 P_{1/2} - 2p^3^2 D_{3/2}^o$ transition at 602.2 Å was used for the lifetime measurement. Using theoretical data from Dankwort and Treffitz [35] we obtain, by interpolation, a branching ratio of 0.17 for this transition. This yields an experimental f -value of 0.091 ± 0.010 . Here the $2s2p^2^2 S_{1/2} - 2p^3^2 D_{3/2}^o$ branch has been neglected since no transition probability for this decay is given in Ref. 35. From Fawcett's calculated values [34] a branching ratio of 0.18 is obtained for the transition under study. From his data can also be concluded that the transition to the $2s2p^2^2 S_{1/2}$ level neglected above only amounts to 0.6 % of the total decay probability for the $2p^3^2 D_{3/2}^o$ level.

Table II

Ion	Transition	Wavelength (Å)	Lifetime of upper level (ns)		Oscillator strength	
			Present work	Theory	Present work	Theory
Al XI	$2s\ 2s\ 2p\ 2p\ 2p\ 3/2$	550.0	1.19 ± 0.05	$1.18^a, 1.18^b, 1.24^c,$ $1.16^d, 1.18^e, 1.18^f$	0.076 ± 0.003	$0.077^a, 0.077^b, 0.073^c,$ $0.078^d, 0.077^e, 0.077^f$
	$2s\ 2s\ 2p\ 2p\ 2p\ 1/2$	568.1	1.35 ± 0.06	$1.27^a, 1.27^b, 1.31^c,$ $1.27^d, 1.27^e, 1.27^f$	0.036 ± 0.002	$0.038^a, 0.038^b, 0.037^c,$ $0.038^d, 0.038^e, 0.038^f$
Al X	$2s2p\ 3p_2^o - 2p^2\ 3p_2$	401.2	0.19 ± 0.03	$0.21^d, 0.22^g, 0.21^h,$ 0.21^i	0.094 ± 0.015	$0.089^d, 0.081^g, 0.085^h,$ 0.085^i
	$2s2p\ 1p_1^o - 2p^2\ 1D_2$	670.1	1.03 ± 0.05	$1.09^c, 1.00^d, 1.06^g,$ $1.01^h, 0.99^i$	0.107 ± 0.005^j	$0.103^c, 0.112^d, 0.106^g,$ $0.109^h, 0.113^i$
Al IX	$2s2p\ 2p_{3/2}^o - 2p^3\ 2p_{1/2,3/2}^o$	437.9	0.093 ± 0.009	$0.078^d, 0.083^i,$ 0.087^k	-	-
	$2s2p\ 2p_{1/2}^o - 2p^3\ 2D_{3/2}^o$	602.2	0.19 ± 0.02	$0.19^d, 0.19^i, 0.21^k$	0.091 ± 0.010^l	$0.100^d, 0.105^i, 0.088^k$
^a Kim and Desclaux [27]		^b Armstrong et al. [28]	^c Safronova et al. [29]	^d Atomic Trans. Prob. [30]		
^e Martin and Wiese [25]		^f Lindgård and Nielsen [31]	^g Victorov and Safronova [32]	^h Mühlethaler and Nussbaumer [33]		
ⁱ Fawcett [34]		^j Branching ratio from Ref. 32	^k Dankwort and Trefftz [35]	^l Branching ratio from Ref. 35		

The study of forbidden transitions is the subject of Papers 4,7,8 and 9. In all cases the transition probabilities for the forbidden decays were determined indirectly (see below).

Forbidden decays, including intercombination lines, are of importance for the diagnostics of astrophysical and laboratory plasmas. The intercombination lines in the spectra of light elements are also of considerable theoretical interest. In the Be I isoelectronic sequence, for instance, the spin-orbit interaction mixes $^1P_1^o$ and $^3P_1^o$ levels, making possible a transition from a $^3P_1^o$ level to the ground level $2s^2\ ^1S_0$. For the 2s2p configuration, this interaction is weak due to the large energy separation between $^1P_1^o$ and $^3P_1^o$; hence the probability for transition to the ground level is low. This fact limits beam-foil studies to very highly ionized members of the sequence, where the lifetimes are reasonably short. Dietrich et al. have measured the 2s2p $^3P_1^o$ lifetime in Fe XXIII [37] and Kr XXXIII [38]. These are the only experimental results available at present. In Paper 4 another intercombination transition in the Be I sequence was investigated, namely the $2s^2\ ^1S_0 - 2s3p\ ^3P_1^o$ transition. In this case the $^1P_1^o - ^3P_1^o$ separation is considerably smaller, making experimental determinations of the intercombination transition probability possible already for low ionization stages. This transition probability has been determined in N IV, O V and F VI. Since the $2s^2\ ^1S_0 - 2s3p\ ^3P_1^o$ transition itself was outside the wavelength range of the monochromator used, another decay branch, the $2s3s\ ^3S_1 - 2s3p\ ^3P_1^o$ transition, was studied. The lifetimes of the $2s3p\ ^3P_{0,1,2}^o$ levels were measured individually and quantitative information about the $2s^2\ ^1S_0 - 2s3p\ ^3P_1^o$ transition probability was then obtained by comparing the $^3P_1^o$ lifetime with those of $^3P_0^o$ and $^3P_2^o$. At the time of this experiment, no theoretical predictions for the $2s^2\ ^1S_0 - 2s3p\ ^3P_1^o$ transition probability had been made. Multiconfiguration Hartree-Fock (MCHF) calculations performed by us supported the experimental results. Later, however, more comprehensive calculations have been carried out by Hibbert [39,40] giving results in good agreement with the experimental values. It should be noted here

that the experimental values quoted in Table 2 of Ref. 39 and Table 5 of Ref. 40 for the lifetimes of $2s3p\ ^3P_0^o$ and $^3P_2^o$ should be interchanged.

In Paper 4 is also reported a determination of the wavelength of the $2s3s\ ^3S_1 - 2s3p\ ^3P_0^o$ transition in F VI which we claimed then to be the first measurement of this wavelength. However, it was subsequently ascertained that this line had been observed previously by Kaufman et al. [41] who determined the wavelength to $2327.28 \pm 0.02\ \text{\AA}$, with which our value of $2327.23 \pm 0.05\ \text{\AA}$ is in good agreement.

A one-photon electric dipole (E1) transition between two levels with zero total angular momentum is strictly forbidden. However, for an atom with non-zero nuclear spin I , this selection rule concerns $I + J$, so two $J = 0$ levels can be connected through hyperfine mixing. In the He I isoelectronic sequence Mohr [42] has theoretically analysed the nuclear-spin-induced decay mode $1s^2\ ^1S_0 - 1s2p\ ^3P_0^o$ for ions in the range $Z = 9$ to 29. When $I = 0$ the $1s2p\ ^3P_0^o$ level decays by E1 radiation to $1s2s\ ^3S_1$ or by a multi-photon process to the ground level. When I differs from zero hyperfine mixing occurs between states with $F = I$ (the hyperfine interaction is diagonal in $F = I + J$, and in this case $J = 0$) of mainly the $1s2p\ ^3P_0^o$, $^3P_1^o$ and $^1P_1^o$ levels. For the $^3P_1^o$ level, the spin-orbit interaction opens the decay channel $1s^2\ ^1S_0 - 1s2p\ ^3P_1^o$ through mixing of the $^3P_1^o$ level with the $np\ ^1P_1^o$ series. The probability for this intercombination transition scales approximately as Z^{10} [43]. Hence, for $Z > 6$ [44] this decay mode dominates over the allowed E1 transition $1s2s\ ^3S_1 - 1s2p\ ^3P_1^o$. The result is a shortening of the $^3P_1^o$ lifetime. Through the hyperfine mixing then the lifetime of the $^3P_0^o$ level is shortened.

The hyperfine quenching effect also arises for the $^3P_2^o$ level through mixing of the appropriate hyperfine components of $^3P_2^o$, $^3P_1^o$ and $^1P_1^o$, resulting in E1 transitions for these F components of $^3P_2^o$ to the ground level. Since these components have different lifetimes the resulting decay curve will be a composite of several exponentials which complicates the analysis. The hyperfine-quenching effect is also much smaller for the $^3P_2^o$ level than for $^3P_0^o$ due to

the much larger ${}^3P_2^o - {}^3P_1^o$ fine structure splitting compared to the ${}^3P_1^o - {}^3P_0^o$ one. However, qualitative evidence for the effect has been obtained by Gould et al. [45], who have studied the decay of the $1s2p\ {}^3P_2^o$ level in He-like V XXII.

In Paper 7 we reported on the first evidence for the quenching of the ${}^3P_0^o$ level. Here lifetime measurements were presented for the $1s2p\ {}^3P_0^o$ and ${}^3P_2^o$ levels in He-like Al XII. The lifetime obtained for the ${}^3P_0^o$ level is in very good agreement with Mohr's calculated value, which also is the case for the value derived for the hyperfine quenching. For the $1s2p\ {}^3P_2^o$ level no effect could be seen. The experimental lifetime is in good agreement with theories not considering hyperfine quenching. A more recent calculation by Tunnell et al. [46] gives the lifetime 5.4 ns for the ${}^3P_2^o$ level, in perfect agreement with our experimental value. The $1s2p\ {}^3P_1^o$ lifetime was not measured since the $1s2s\ {}^3S_1 - 1s2p\ {}^3P_1^o$ transition could not be observed. The reason for this is the dominant intercombination transition $1s^2\ {}^1S_0 - 1s2p\ {}^3P_1^o$ mentioned above. This transition, which falls in the X-ray region, has a probability about 500 times higher than the allowed E1 transition [47]. By observing this decay branch the lifetime of the ${}^3P_1^o$ level in He-like Al has recently been measured by Armour et al. [48], who obtained the result 12.8 ± 0.7 ps for Al. The line which was assigned to the $1s2s\ {}^3S_1 - 1s2p\ {}^3P_1^o$ transition in Paper 5 was later identified as the hydrogenic transition $n = 7 - 9$ in Al XI.

The result for the ${}^3P_0^o$ level was confirmed by a similar experiment in He-like F VIII, which is described in Papers 8 and 9. An earlier experiment by Mowat et al. [49] failed to detect the hyperfine quenching due to a too large experimental uncertainty. It is seen in Table 1 of Paper 8 and Table I of Paper 9 that if the hyperfine quenching calculated by Mohr [42] is combined with an interpolated value from the relativistic calculations by Lin et al. [47] for the $1s2s\ {}^3S_1 - 1s2p\ {}^3P_0^o$ transition probability, perfect agreement is obtained with our experimental lifetime. Neither in the case of F VIII could any quenching effect be observed in the lifetime of the ${}^3P_2^o$ level.

Paper 9 is an extension of the work in Paper 8. We report accurate lifetimes for all $1s2p\ ^3P_{0,1,2}^o$ levels in F VIII and for $1s2p\ ^3P_{1,2}^o$ in O VII. From the data obtained, experimental transition rates for the $1s^2\ ^1S_0 - 1s2p\ ^3P_1^o$ intercombination line are deduced for both O VII and F VIII. The results are in good agreement with recent theoretical calculations. The $^3P_2^o$ and $^3P_0^o$ lifetimes in F VIII have already been discussed above.

One of the problems encountered in the development of controlled fusion devices is the presence of impurities in the plasma. It has been found [50-53] that heavy metal impurities, even in concentrations as small as a fraction of a percent, have a pronounced detrimental effect on the plasma behaviour. The elements involved are those which appear in the construction materials which are used in first walls, limiters and divertors in tokamaks. These elements reach high stages of ionization in the high-temperature plasma. Usually the spectra for these highly-ionized species are very complex, but for ions belonging to certain isoelectronic sequences, e.g. the Li-, Be-, Na-, Mg-, Cu- and Zn-sequences, the spectra become fairly simple. Spectra belonging to these sequences have been observed in tokamak plasmas by several authors [54-56].

Among the most important types of data needed to analyse the plasma-impurity problems are atomic oscillator strengths and excitation rate coefficients [57,58]. The isoelectronic sequences mentioned above are particularly important due to the fact that the excitation rates for the resonance lines are very large because of the relatively low excitation energy of the first excited states and the rather large oscillator strengths. Thus, these resonance transitions give significant contributions to the radiative energy losses in the plasma.

A recent theoretical investigation by Curtis and Ellis [59] predicts that highly ionized members of the Pm I sequence should exhibit strong resonance lines in the spectra of hot plasmas contaminated by heavy elements, since these ions for $Z \geq 74$ (W XIV) have an alkali structure with the ground con-

figuration $4f^{14}5s$ according to Hartree-Fock calculations with relativistic corrections. So far this has not been verified experimentally.

Systematic trends for the oscillator strengths of the resonance transitions in some of the isoelectronic sequences mentioned above, especially the one- and two-valence-electron sequences [57,60-62] show large discrepancies between beam-foil experimental data and theoretical calculations for several multiply-ionized members of the sequences. It has been suggested that part of this discrepancy originates from the fact that lifetime measurements for the first excited levels of these sequences may be strongly affected by severe cascading from higher-lying levels [57,60-63]. However, if the decay of the primary level and all of the significant cascade levels are measured, the Arbitrarily-Normalized Decay Curves (ANDC) method [64] can be used. Lifetime measurements for the most important cascading levels require a detailed knowledge of the level scheme. In the case of the Zn I sequence, level schemes are incompletely known even for rather low members of the sequence. In this sequence, with the resonance transition $4s^2\ ^1S_0 - 4s4p\ ^1P_1^o$, the $^1P_1^o$ level may be strongly repopulated by transitions from the lower members of the $4sns$ and $4snd$ series and also from the doubly-excited $4p^2$ configuration. In a comparison with the analogous Mg I sequence the isoelectronic diagram indicated that the levels $4s4d\ ^1D$ in Ge III through Se V given in Atomic Energy Levels (AEL) [65] should be given the designation $4p^2\ ^1D$, and that the levels reported in AEL as $4p^2\ ^1D$ in Ge III and $4p^2\ ^1D$ and 1S in As IV most probably should be discarded. Consequently, one of the two 1D levels of $4s4d$ and $4p^2$ was missing throughout the sequence. To establish the missing 1D level in Ga II a combined investigation using a sliding spark source and beam-foil excitation was carried out. This work is reported in Paper 3. In Ga II, configuration interaction strongly mixes the two 1D levels, making the designation arbitrary, as has been shown in the MCHF calculations by Froese-Fischer and Hansen [66].

The gallium spark spectrum was recorded in the wavelength region 800 - 2500 Å with a photographic 3 m normal incidence vacuum spectrograph, equipped

with a MgF_2 -coated aluminium replica grating with 1200 grooves/mm. Four new Ga II-lines were found, two of them leading to the establishment of the missing ^1D term which was designated $4s4d\ ^1\text{D}$, while the previously known ^1D level was changed to $4p^2\ ^1\text{D}$. The remaining two lines were tentatively identified as the $4s4p\ ^1\text{P}_1^o - 4p^2\ ^1\text{S}_0$ and $4s4p\ ^1\text{P}_1^o - 4s6s\ ^1\text{S}_0$ transitions giving the new level values listed in Table 2 of Paper 3. Beam-foil measurements were made of the lifetimes of the $4p^2\ ^1\text{D}$ and $4s4d\ ^1\text{D}$ levels. Table III shows the results together with more recent experimental results and also theoretical calculations by Froese-Fischer and Hansen [66]. The lifetimes have been converted to f -values under the assumption that the decay to $4s4p\ ^1\text{P}_1^o$ is the only decay channel.

Table III

Level	Lifetime (ns)	f -value	
		Experiment	Theory
$4p^2\ ^1\text{D}_2$	54 ± 5^a	0.034 ± 0.003^a	$0.002(1)^c$
	55 ± 5^b	0.033 ± 0.003^b	$0.011(v)^c$
$4s4d\ ^1\text{D}_2$	0.73 ± 0.07^a	1.11 ± 0.11^a	$1.21(1)^d$
	0.76 ± 0.07^b	1.07 ± 0.10^b	$1.22(v)^d$

^aThis work
^bAndersen et al. [67]
^cFroese-Fischer and Hansen [66], relativistic value
^dFroese-Fischer and Hansen [66], non-relativistic value

A study of the resonance transition, $4s^2\ ^1\text{S}_0 - 4s4p\ ^1\text{P}_1^o$, in Ga II is presently being done. Beam-foil decay curves have been recorded for the upper level and the four most prominent cascades, namely from the levels $4s4d\ ^1\text{D}_2$, $4s5s\ ^1\text{S}_0$, $4p^2\ ^1\text{D}_2$ and $4p^2\ ^1\text{S}_0$. An ANDC-analysis has been performed using the computer-program CANDY [68] yielding a preliminary lifetime for the $4s4p\ ^1\text{P}_1^o$ level of 0.41 ± 0.03 ns. This result should be compared with the value 0.65 ± 0.03 ns which we obtain from a multi-exponential fit utilizing the program

DISCRETE [26]. A previous beam-foil measurement of the $4s4p\ ^1P_1^o$ level lifetime, made by Andersen et al. [67], gave the result 0.49 ± 0.04 ns. These investigators studied the excitation functions for the $4s4p\ ^1P_1^o$, $4s5s\ ^1S_0$ and $4s4d\ ^1D_2$ levels and found that the contributions from the two cascades could be efficiently reduced if the $4s4p\ ^1P_1^o$ level lifetime was measured at a sufficiently low energy. However, the contribution from the $4p^2\ ^1S_0$ level was not taken into consideration in their work. The lifetime of this level has been measured by us to 0.55 ± 0.06 ns (preliminary value), thus it has a lifetime comparable to that of the $^1P_1^o$ level itself. The neglect of this cascade in Ref. 67 may therefore well explain the difference between their result for the $^1P_1^o$ lifetime and our. Further analysis of the $^1P_1^o$ decay is in progress and the final result will be reported elsewhere [69] along with comparison with various theoretical calculations.

The first measurements of the lifetimes of the first excited levels in Cu-like Mo XIV are presented in Paper 12. References to previous studies in Mo XIV are given in the paper. Spectra in the grazing-incidence region were recorded at every 5 MeV between 5 and 25 MeV and are shown in Fig. 2.

The analysis of the decay curves for the $4p\ ^2P^o$ levels in the present work posed a special problem. The decay is known to be affected by cascades as discussed above. Indeed, a standard multi-exponential analysis yielded lifetimes 20 - 25 % longer than predicted by theory. The limited spectral resolution prevented the use of the ANDC method [64] for the lifetime analysis since the cascading transitions were affected by blends. Instead our experimental decay curves were fitted with a variable primary decay and a fixed theoretically derived cascade part. The cascade part consisted of the contributions from the yrast chain. These levels, with $\ell = n - 1$, are known to be efficiently populated by the beam-foil interaction mechanism, and their decay has a dominant effect on the decay curves for the first excited levels [60, 61]. A Gaussian slit function was also included in the decay function.

The assumption of a relative initial population of the levels proportional

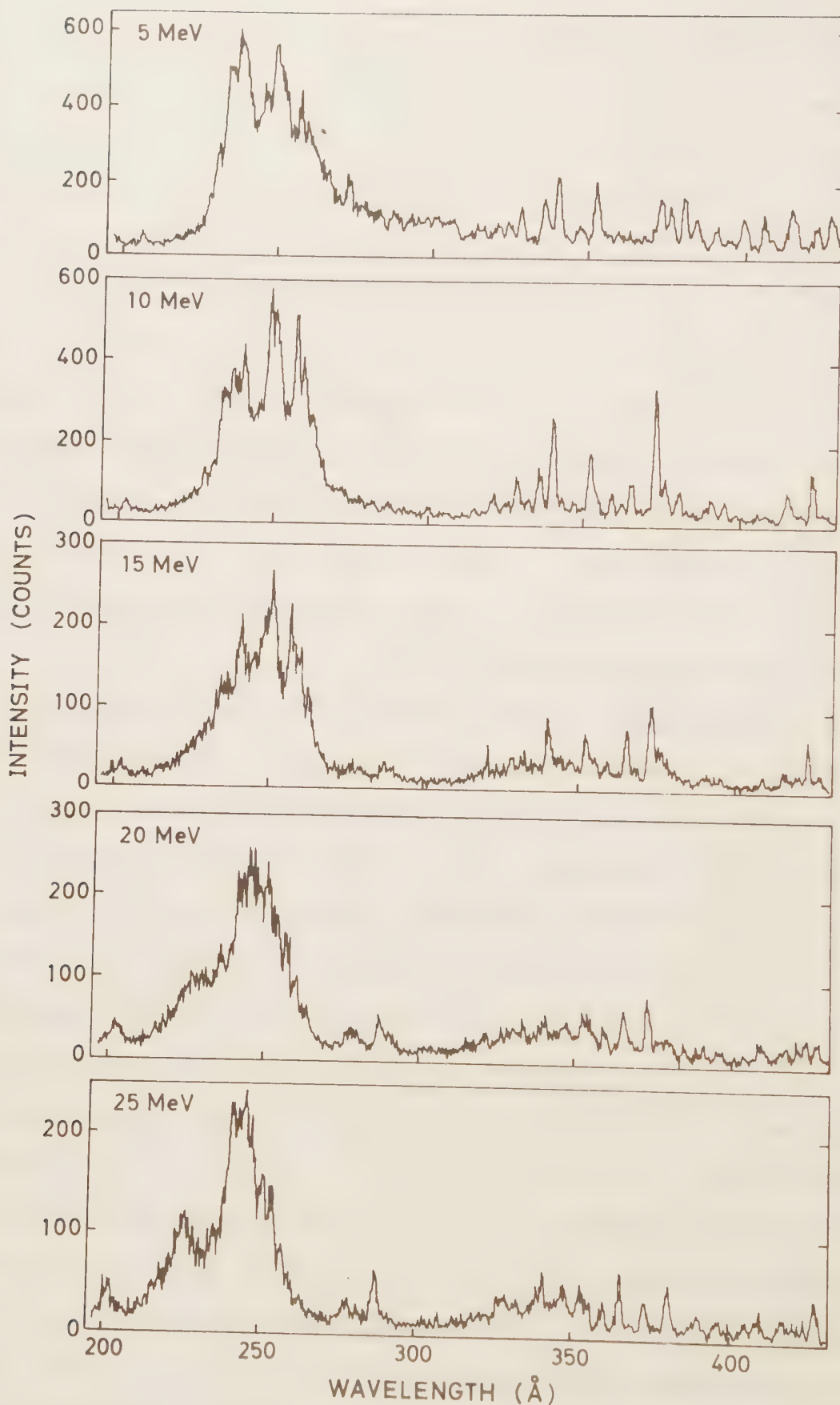


Fig. 2. Beam-foil spectra of Mo at 5 to 25 MeV beam energies in the wavelength region 195 - 430 Å.

to $(2\ell + 1)(n^*)^{-3}$, where n^* is the effective quantum number, gave a good representation of the data. With this population model the very long tails which were observed in the curves over 40 - 50 decay lengths could be produced. However, this population model is unrealistic, since when summed over all n and ℓ values it diverges and thus has to be truncated at some arbitrary value of n , which in this case was set to $n = 20$. A cutoff at this particular value of n was motivated by the fact that for levels around $n = 20$ one decay-length is of the same order as the observation length.

Cascade modelling for the resonance transitions in Cu-like Kr VIII have been made by Younger and Wiese [63], who used a truncated $(2\ell + 1)(n^*)^{-3}$ population and by Livingston et al. [70], who found a population proportional to $(2\ell + 1)(n^*)^{-2}$, truncated at $n = 26$, to give the best fit to the data. The $(2\ell + 1)(n^*)^{-2}$ model also gave the best fits to the decays of the $3p\ ^2P^o$ and $3d\ ^2D$ levels in Na-like Fe XVI, which have been investigated by Buchet et al. [71]. In a recent work by Hultberg and coworkers [72] on Zn II, it was found that the decay curves for the $4s - 4p$ resonance transitions could be described by a $(n^*)^{-5}$ population model, whereas the model $(2\ell + 1)(n^*)^{-5}$ rather well approximated the decay curves for the $4d$ and $4f$ levels. Still other models were used by Armour et al. [48] in their study of the decay of the $1s2p\ ^3P_1^o$ level in He-like Mg and Al, and by Träbert [73] in his study of highly-ionized Si. These examples show that so far no population model that can be applied to a large number of systems has been obtained.

In connection with the lifetime measurements for the $4p$ levels in Mo XIV also the decay curve for the $4s^2\ ^1S_0 - 4s4p\ ^1P_1^o$ resonance transition in Zn-like Mo XIII was recorded. A decay curve at 10 MeV is shown in Fig. 3. This line at 341 Å was first observed in the Princeton ST tokamak [54,56] and later by means of a low-inductance open spark by Reader and Acquista [74]. The spectrum of Mo XIII is very incompletely known. Apart from the resonance transition the only observed transitions are the $4s^2\ ^1S_0 - 4s5p\ ^1P_1^o$, $^3P_1^o$ and $4s4p\ ^3P_{0,1,2}^o - 4s5s\ ^3S_1$ ones [75] and the transitions $3d^{10}4s^2 - 3d^94s^24p$ re-

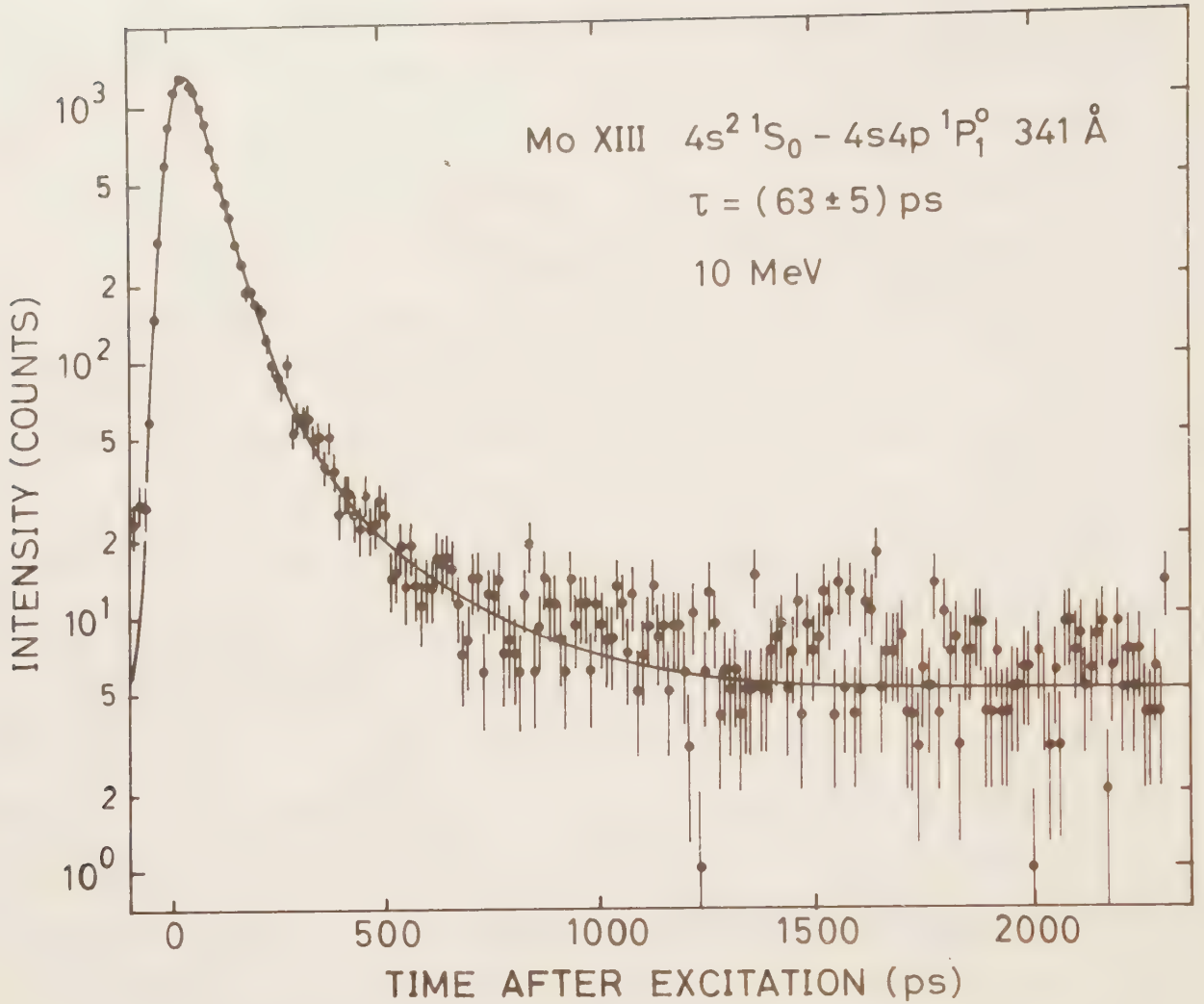


Fig. 3. Decay curve for the $4s4p\ ^1P_1^o$ level in Mo XIII at 10 MeV beam energy. The solid curve is a multi-exponential fit to the experimental data including the slit function.

sulting from the excitation of a 3d electron which have been studied by Burkhalter et al. [76] and by Wyart et al. [77]. Thus none of the primary cascades to the resonance transition have been observed, making it impossible to analyse the decay by means of the ANDC method. Since a decay curve simulation like the one above requires a detailed knowledge of energy level values as well as transition probabilities such an analysis could not be carried out either. Moreover, the $4s4p\ ^1P_1^o$ level is fed from doubly-excited levels, such as the $4p^2\ ^1D_2$ with its yrast chain, a fact complicating a cascade modelling since it is not known how the doubly-excited levels are populated. Nevertheless, such an attempt has been made for the decay of $4s4p\ ^1P_1^o$ in the isoelec-

tronic Kr VII [78], where a simulated curve including the $4sn\ell$ yrast chain up to $n = 12$ and the $4p^2\ ^1D$ and $\ ^1S$ levels with a population proportional to $(2\ell + 1)(n^*)^{-3}$ agreed well with the experimental curve at short decay times but was unable to reproduce the long-time behaviour of the experimental curve.

Applying a multi-exponential fit to our Mo XIII data, we obtained a lifetime of 63 ± 5 ps, yielding an f -value of 0.83 ± 0.07 . This f -value is about a factor of two lower than predicted by various theoretical calculations [79-83], consistent with the observed trend for this sequence [57,62].

4. THE BEAM-FOIL EXCITATION MECHANISM

4.1 General

The beam-foil interaction can be separated into two parts - the interaction at the two surfaces and that within the bulk of the foil.

4.1.1 The surface interaction

At the first surface of the foil electrons are stripped off or added to the incoming projectile since the charge state of this is usually not the equilibrium charge state within the foil.

At the exit surface the excitation of Rydberg levels is believed to take place through an electron pick-up process [84-86]. These levels are of geometrically large size and cannot exist in unperturbed eigenstates inside the foil.

Due to the high electric resistance of the carbon foil stray electric fields may be built up in the vicinity of the exit surface of the foil. These fields have been shown to affect the intensity and polarization of the emitted light in beam-foil spectroscopy (see e.g. [87]). These microfields may also prevent the existence of ions in very high n states [63].

4.1.2 The bulk interaction

As the projectile moves through the solid foil, it undergoes multiple collisions and thus loses energy.

It has been put forward [88] that the lowest-lying levels in an atom or ion, which are geometrically small, are selectively populated through inner-shell excitations inside the foil, an observation which is explained in terms of the molecular-orbital electron-promotion picture (see references given in [88]).

4.2 The population of levels

A detailed knowledge about the population of levels after beam-foil exci-

tation is of importance for the understanding of the excitation mechanism. As has been pointed out above (in connection with the analysis of the decay data for the $4p\ ^2P^o$ levels in Mo XIV), relative populations of levels are also needed for modelling of decay curves in situations where e.g. the ANDC method cannot be used.

In Paper 11 we have studied the relative populations in beam-foil excited C IV, N V, O VI and F VII in the range $n = 3 - 12$. We observed that in the less ionized species C IV and N V the relative level population for a fixed value of ℓ decreased with n , whereas medium to high-lying levels in the more strongly ionized species O VI and F VII were preferentially populated. If the population distribution curves are viewed as portions of imagined extended curves with a soft maximum, then O VI has its maximum at $n \sim 7$, F VII at $n \sim 8$, N V probably at $n \sim 6$ (or $5 - 6$) and the imagined maximum for C IV is at about $n \sim 5$. These levels have binding energies around 10 eV, as do the valence electrons of the carbon foil. Thus, the behaviour of the population distribution curves may be explained by preferred resonance charge transfer of a foil valence-band electron to the projectile.

Recently, the relative level populations in beam-foil excited Ar VIII and Kr VIII have been studied [88]. A strong maximum for levels with $n \sim 11$ was found, corresponding to a binding energy of about 10 eV. For neutral and weakly ionized atoms, the level population within a Rydberg series has been found to exhibit a power-law decrease [89]. However, in these cases, the levels studied had binding energies of less than 10 eV. Thus there is no contradiction between the preferential excitation of high-lying levels in highly-ionized atoms and the observed power-law decrease for neutral and weakly-ionized ones.

In Paper 11 we also observed that, for a fixed value of n , the population increased with ℓ , in agreement with observations in neutral and few times ionized elements [89]. In addition, the p levels were overpopulated, especially in O VI.

4.3 Polarization

The fact that the beam-foil source geometry has one unique spatial axis - the beam axis (usually also the normal to the foil) - and hence has cylindrical symmetry causes the ions generally to be anisotropically excited. This anisotropy manifests itself as polarization of the emitted light. If the foil is tilted with respect to the beam axis, the cylindrical symmetry is lost, with a corresponding change in polarization.

The anisotropy is usually represented in terms of atomic alignment and orientation which express different kinds of non-statistical population of the magnetic sublevels of the angular momentum of the atom. By alignment is meant that magnetic sublevels with the same absolute value of m_L are equally populated. Alignment gives rise to linear polarization. Orientation means that a single magnetic sublevel is preferentially populated with respect to some equilibrium value. This gives rise to circularly polarized light. Orientation can only be produced with the tilted-foil geometry in the beam-foil case.

For the description of polarized light Stokes [90] introduced four parameters, usually labelled I, M, C and S [91]. If a coordinate system (x,y,z) is chosen with x and y perpendicular to the direction of propagation z of the light, and $I(\phi)$ is the intensity of the light polarized in the direction ϕ to the x axis, we have [92]

$$\begin{aligned}
 I &= I(0^\circ) + I(90^\circ) \\
 M &= I(0^\circ) - I(90^\circ) \\
 C &= I(45^\circ) - I(135^\circ) \\
 S &= I(\sigma^+) - I(\sigma^-)
 \end{aligned}
 \tag{9}$$

where $\sigma^\pm$ indicates right or left hand circularly polarized light, respectively. If all four Stokes parameters are to be measured the absolute intensity has to be known. However, the state of polarization is completely determined by the relative Stokes parameters M/I , C/I and S/I .

In Paper 1 we have studied the polarization for the $n = 6 - 7$ transitions

in O VI (3433 Å) and the $2p3p\ ^4D - 2p3d\ ^4F^o$ transitions in O IV (3737 Å) using the method of beam-tilted-foil excitation. With a beam energy of 4 MeV the circular polarization (S/I) for these two lines was measured as a function of the foil tilt angle. The state of polarization of the radiation emitted in a direction perpendicular to the beam and parallel to the foil tilt axis was determined using a UV transmission polarizer, the axis of which was set at angles of -45° , 0° , 45° and 90° relative to a direction parallel to the beam. An achromatic quarter-wave plate could be placed between the beam and the polarizer with its fast axis parallel to the beam. Instrumental polarization was eliminated through the use of a Hanle depolarizer. A substantial circular polarization was found at large tilt angles for both transitions studied. The angular dependence found was similar to earlier findings (see references given in Paper 1). A preliminary investigation at a higher beam energy indicated a decrease in orientation for the O VI 3433 Å line.

Later, the manually operated optical system used in Paper 1 has been replaced by an automated system [93] which allows simultaneous measurement of all three relative Stokes parameters [92]. In this system the quarter-wave plate is rotated step-wise by means of a computer-controlled stepping motor, while the linear polarizer is kept fixed. Using this automated system the results in Paper 1 have been confirmed and also the uncertainty in the measurements has been considerably decreased [94].

5. FAST-BEAM LEVEL-CROSSING SPECTROSCOPY

5.1 General

If an atom is placed in an external magnetic field, the energy levels are split up into Zeeman sublevels. When the magnetic field strength is increased points may be reached at which two excited sublevels cross. At such a point interference phenomena in the resonance fluorescence of the atom can occur. For field strengths at which the sublevels are well separated, each level contributes separately to the resonance scattering (incoherent scattering). In the range where the two excited levels overlap within their natural width (since the levels have a finite lifetime they are not sharp but possess a Heisenberg fuzziness given by the lifetime), the two levels may be coherently excited causing an interference in the scattered light. When sweeping the magnetic field through such a level-crossing (LC) a resonance signal will be obtained. Depending on the direction and polarization of the incoming and outgoing photon this signal will be either a pure Lorentzian or a pure dispersion curve or a mixture of both. The theory of the LC phenomenon has been given by Breit [95] and Franken [96]. The first LC spectroscopy experiment was carried out by Colegrove et al. [97], who utilized this technique for the determination of the $1s2p\ ^3P_1^o - ^3P_2^o$ separation in He I.

The LC technique is a high-resolution technique, its precision only being limited by the natural line width. It can be used e.g. for determining fine and hyperfine structures, Landé g-factors and lifetimes of excited states.

A special case is the LC at zero magnetic field. This effect was first observed by Hanle in 1924 [98].

In the classical LC setup a vapour of the atoms to be studied is contained in a glass or quartz cell which is placed in a homogeneous and variable magnetic field. The cell is then irradiated by resonance light from a spectroscopic lamp.

In the fast-beam LC technique collisions between the beam particles and a gas is utilized to populate the excited levels in the beam ions. This techni-

que makes LC experiments possible for highly excited singly or doubly ionized atoms. Also a wider variety of elements can be studied through the use of an ion accelerator.

5.2 Result

In Paper 10 we have measured the fine structure in the $nd\ ^2D$, $n = 4,5$ and $nf\ ^2F^o$, $n = 4,5,6$ levels in Be II using the fast-beam LC method. The beryllium ions, emerging from an isotope separator, were excited by collisions with He atoms in a cell. This cell was placed between the poles of an electromagnet, the magnetic field being perpendicular to the ion beam as well as to the direction of observation of the emitted light. During the passage of the ions through the magnetic field, a motional electric field will be created. This electric field, oriented perpendicularly both to the magnetic field and the ion beam, was compensated for by means of a pair of electric field plates, placed inside the cell. The voltage applied on these plates could be varied so as to practically eliminate the motional electric field.

The purpose of this experiment was to test the possibility of deviations from hydrogenic behaviour in the fine structures in simple alkali-like systems. Such deviations have been observed in the fine structure of Rydberg levels in the heavier alkali-like atoms, e.g. the inverted $nd\ ^2D$ fine structure. This feature has been explained theoretically [99,100] as being due to a strong exchange-core polarization of the p core induced by the Rydberg electron. In Li-like atoms, however, no p electrons are present and deviations from hydrogenic fine structure could then be attributed to correlation effects involving the $(1s^2)$ core.

In the present work, the fine structure splittings mentioned above have been determined with a precision of 10^{-3} . Within this accuracy, the $nd\ ^2D$, $n = 4,5$ levels were hydrogenic. For the $nf\ ^2F^o$ series, we found the fine structure splitting of the $4f\ ^2F^o$ level larger than the hydrogenic value, whereas $n = 5$ and 6 were hydrogenic within the error limits. Thus the present

study indicated the normal fine structure in Be II and supported the suggestion that the inversion of the fine structure in the alkali atoms with p cores is due to exchange-core polarization. The small deviations from hydrogenic fine structure could be attributed to correlation effects involving s-type excitations in the core.

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ERRATA

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		r10 ⁻	states	stages	
	58	ℓ2 ⁺	states	stages	
<u>Paper 3</u>	Superscript "o" is consistently being written as "0"				
<u>Paper 4</u>	88	ℓ9 ⁺	for	of	
		ℓ23 ⁻	Dietrich et al.,	Dietrich et al.	
		ℓ5 ⁻	astrophysical	astrophysical plasmas	
		r8 ⁺	for	of	
	89	r2 ⁺	on	in	
	90	footnote a	discussions	discussion	
	91	ℓ17 ⁺	being not	not being	
	<u>Paper 5</u>	C1-183	ℓ7 ⁺	beam foil	beam-foil
			Text, Fig.1, 1 ⁺	vaccum	vacuum
		C1-184	ℓ6 ⁺	2s2p ¹ P ₁	2s2p ¹ P ₁ ^o
ℓ15 ⁻			2p ² P _{3/2}	2p ² P _{3/2} ^o	
ℓ14 ⁻			2p ² P _{1/2}	2p ² P _{1/2} ^o	
ℓ8 ⁻			agrees	agree	
		Fig.3	(MM)	(mm)	
		r4 ⁺	0.047 ± 0.007	0.094 ± 0.015	
C1-185		Table I should be replaced by the revised and somewhat extended Table II on page 26 of the summary. See also the discussion of the results in the summary.			
		ℓ5 ⁻	are	is	
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<u>Paper 6</u>	151	$\ell 13^-$	line	lines
	152	$r12^+$	2895.2 ± 0.03	2895.2 ± 0.02
		Table I col.5, 16^+	3433.59	3433.00
		col.5, 17^+	3422.59	3433.59
	153	$\ell 9^-$	$A(Z) = \frac{9}{2} \left(\frac{Z-1}{Z} \right)^2$	$A(Z) = \frac{9}{2} \left(\frac{Z-1}{Z} \right)^2$
		$\ell 8^-$	$k(Z) = \frac{10}{2} \left(\frac{Z-1}{Z} \right)^2$	$k(Z) = \frac{10}{3} \left(\frac{Z-1}{Z} \right)^2$
		$\ell 3^-$	Bucket	Buchet
	154	Fig.2	(MM)	(mm)
<u>Paper 7</u>	45	headline	Al XIII	Al XII
	47	Table III, 1^+	separation	separation
		Ref.1	..	.
		Ref.5	(eds)	(eds.)
	48	Ref.15	Estermann, J.	Estermann, I.
<u>Paper 8</u>	L145	21^-	1455	1454
<u>Paper 9</u>	570	9^-	possible but	possible for $Z > 16$ but
	571	$r18^-$	of	from
	572	$r25^+$	also here	here also
	573	$\ell 3^-$	resulting	result
		$r18^-$	analyses	analysis
		$r17^-$	calculations	calculations.
		footnote j	Selling	Sellin
	574	$\ell 1^+$	Mohrs	Mohr's
<u>Paper 10</u>	215	$\ell 9^+$	50 keV of	50 keV
		$r15^-$	eliminated	reduced
		$r14^-$	to be	to
	216	$\ell 3^-$	decays at	decays to $2p \ ^2P$ at
		$r11^- - 10^-$	With the p electrons in the core eliminated	With no p electrons in the core

	Page	Line/equiv.	Replace	by
<u>Paper 11</u>	479	210^-	ions	atoms
	483	Ref. 24 should be replaced by Ref. 24': S.M. Younger and W.L. Wiese, Phys. Rev. A <u>17</u> , 1944 (1978)		
<u>Paper 12</u>	1230	Text, Fig.1, 1^-	transitions	transition
	1233	Ref.28	Springer	Springer-Verlag

